Evaluation of airborne transmission risk in university towns based on IEQ surveys

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ABSTRACT

This study aims to evaluate airborne transmission risk in university towns during the COVID-19 pandemic based on surveys of indoor environmental quality (IEQ). Both on-site measurements and questionnaire surveys were carried out in public buildings in university towns in Changsha, China. Air temperature, relative humidity, and CO_2 concentration in one library, ten classrooms, eight canteens, seven restaurants, and sixteen malls were measured. 2220 valid questionnaires concerning occupants' sensation on thermal environment, air movement, and indoor air quality were collected. A 3-level evaluation method of airborne transmission risk that is dependent on building type and indoor CO_2 concentration was developed. Excessive CO_2 concentration is found in library (1045 ppm), classrooms (1151 ppm), restaurants (1242 ppm), and malls (1057 ppm). The percentage time of "high risk" accounts for 18–100% in these buildings. The results reveal a serious problem: numerous public buildings in China and probably other resource limited countries are not basically prepared and equipped to cope with airborne transmission. This fact should be taken into account when developing guidelines and formulating mitigation measures. Real-time monitoring and displaying IEQ and thus the transmission risk level should be an important way to be widely implemented in public buildings.

1. Introduction

The public buildings in university towns, mainly including libraries, classrooms, canteens, restaurants and malls, are where students and teachers spend their majority of time. The IEQ of these public buildings is a crucial factor affecting the comfort and health of students and teachers [1, 2]. Indoor air temperature, relative humidity (RH), air speed, and indoor air quality (IAQ) are the most important parameters of IEQ. It has been reported that the public buildings in university towns are generally characterized by high occupant density. The density of students in classrooms reached 0.9 person/m^3, and the IAQ in schools was unacceptable due to inadequate fresh air [3]. In addition, more than half of the classrooms have CO_2 levels above 1000 ppm [4, 5]. The combination of high occupant density and insufficient ventilation would put the indoor environments into a high risk of cross-infection during the outbreaks of respiratory infectious diseases.

The severe acute respiratory disease COVID-19, which is caused by the virus SARS-CoV-2, broke out in early 2020 and rapidly spread over the world. To the time of submitting this paper, it has caused more than 20 million confirmed cases and 4 million deaths [6]. During January 26 – February 10 of the year 2020, a small outbreak occurred in a restaurant of Guangzhou, China, causing 10 confirmed cases. Short social distances between diners and poor ventilation were identified as the important driving forces of this outbreak [7]. Starting on February 21, a 16-day SARS-CoV-2 outbreak swept through a call center in South Korea, resulting in the infection of 94 workers. It was found that the infected area was rather concentrated, and the crowded workplaces and the heavy talking were believed to be the reason for this outbreak [8]. It is worth noting that aforementioned outbreaks happened in crowded indoor spaces with relatively poor ventilation, which is the typical characteristics of public buildings in university towns. Shen' study [9] confirmed that universities and restaurants are facing a high risk of airborne transmission. Among others, classrooms and libraries, which are intensively occupied by students, are places of high risk of exposure [10]. Colorado Department of Public Health and Environment (CDPHE) reported that school is one of the places with the highest number of confirmed cases per outbreak, where each outbreak would cause 90 cases on average. The public buildings in university towns therefore present a challenge in the mitigation of COVID-19 transmission [11], which should be paid special attention when formulating control measures for university towns.

There are three confirmed routes that play a decisive role in COVID-19 transmission: (1) fomite through surface contact, which can be effectively dealt with by appropriate surface cleaning hand hygiene; (2) droplet-borne transmission with droplets emitted during human breathing, talking, sneezing and coughing, which can be prevented by face masks and social distance; (3) air-borne transmission, through virus-laden aerosols that can suspend in the air over a long period and are capable of traveling farther than the usual social distances [12]. ASHARE and CDC have raised their concern about air-borne transmission [13, 14]. IAQ control strategies such as ventilation dilution and air cleaning are considered to be efficient solutions to reduce the risk of airborne transmission [15–17]. According to Wells-Riley equation [18, 19], the low infection risk can be realized by increasing the ventilation rate of virus-free air. As important parameters of IEQ, indoor air temperature and RH affect the viability and the evaporation of the droplets [20]. van Doremalen et al. [21] found that the viability of SARS-CoV-2 is high in the indoor environment with air temperature of 21 - 23 °C and RH of 65%. It was reported that the viability of SARS-CoV-2 is reduced from 14 days to 30 mins by rising the air temperature from 4 °C to 56 °C [22]. The average evaporation time of 12 μm droplets under 50% RH is shortened from 1.44 s to 0.42 s, with the air temperature rising from 5 °C to 35 °C [23]. RH has been proven sensitive to many air-borne viruses [24], and an increase in RH would reduce the evaporation speed of a droplet [25]. Wang et al. [26] found 70 - 80% of RH can reduce the number of infected cases. Redrow et al. [27] observed that the time a 10 μm droplet evaporating to a 3.5 μm nuclei shortened from 0.55 s to 0.25 s with RH decreased from 80% to 20%. In general, a well maintained IEQ can help to mitigate the risk of airborne transmission.

Currently, vaccination has been widely implemented to mitigate the spread. However, infection and transmission of COVID-19 are still occurring, due to the rapid mutation of the SARS-CoV-2 virus. The recent Delta variant [28] is much more infectious and spreads much faster than its earlier generations, which also causes more severe symptoms and damages to human body [29]. Therefore, any mitigation measures and restrictions of the pandemic would still need to be implemented for a long time. Since the reopening of the universities worldwide, many governments and professional groups have actions in mitigating the airborne transmission risk in campus. Based on existing air handling units, ASHRAE [30] suggested that the outdoor air should be introduced as the maximum ratio without compromising the thermal comfort of indoor occupants, and dedicated outdoor air systems should be run two hours before and after the occupancy. REHVA [16] recommended that the fresh air should supplied in a ventilation rate of 8–10 L/s/person in classrooms. Taiwan ministry of education [31] suggests classroom windows and transoms should be opened to allow air to circulate, and the dust screen of the ventilation equipment should be cleaned frequently. Exhaust fans should be used as an auxiliary strategy if indoor spaces are confined. Chinese Ministry of Education also published COVID-19 prevention and control guidelines for higher education institutes in March 2020 [32], which suggested that educational buildings should be ventilated at least 3 times per day with each time exceeding 30 mins. If possible, windows can be continuously open to keep the air circulated and to obtain fresh air without compromising thermal comfort. In addition, before and after the serving time, the windows of canteens should be open for 30 mins for ventilation. However, it is unknown if these guidelines are actually followed in practice, to what extent the indoor IEQ is improved by following the guidelines, and how is the IEQ during the pandemic. In such regards, this study investigated five types of public buildings in university town: library, classroom, canteen, restaurant and mall. These public buildings were evaluated through on-site measurements and questionnaire surveys. The transmission risk of SARS-CoV-2 was also evaluated by the IAQ results. This study is intended to reveal the IEQ condition in public buildings in university towns, to identify problems, and to propose possible solutions for improvement, which may eventually contribute to safer universities.

Table 1
Information of the studied buildings.

Building Type	Measuring period	Ventilation strategy
Library	8:00 a.m. to 10 p.m.	Air-conditioners
Classroom	During the class time	Air-conditioners
Canteen	8:30 a.m. to 4:30 p.m.	Natural ventilation
Restaurant	8:30 a.m. to 4:30 p.m.	Air-conditioners or fan-coil units
Mall	10:00 a.m. to 4:30 p.m.	Mechanical ventilation

2. Methodology

2.1. On-site measurements

In this study, on-site measurements and questionnaire surveys were conducted in the public buildings in university town in Changsha (111.53° - 114.15° East, 27.51° - 28.41° North), which is the capital of Hunan province in China, the investigations were conducted during November and December of the year 2020, when the outdoor air temperature was mostly between 11 °C and 18 °C, and RH was between 67% and 76%. The public buildings of 1 library, 10 classrooms, 8 canteens, 7 restaurants and 16 malls were measured, of which typical results obtained in 1 library, 7 classrooms located in 3 buildings (abbreviated as CL-A to CL-G), 4 canteens located in 3 buildings (abbreviated as CA-A to CA-D), 4 restaurants (abbreviated as RE-A to RE-D), and 7 malls (abbreviated as Mall-A to Mall-G) were shown. The location of Changsha and these typical buildings and some of the indoor environments are shown in Fig. 1.

The ventilation strategies were different in these buildings. Mechanical ventilation systems were seldom installed in university public buildings. The university library and classrooms were installed with air-conditioners, which controlled only the indoor air temperature with circulated indoor air [33], and fresh air was obtained via opening the doors and windows, with the open duration and frequency decided by indoor occupants. In canteens, air-conditioners were installed but not used during the measurements (that was a normal condition), and again the fresh air was introduced by natural ventilation that was determined by occupant behavior. In restaurants, the air-conditioners were in operation, and the windows were kept closed during the business hours in order to keep a warm indoor thermal environment, and the fresh air was only obtained by the shortly opened doors when customers entering the restaurants. As for malls, mechanical ventilation with mixing ventilation mode was applied.

Table 1 lists the measuring periods in different types of buildings. Thermal environment and IAQ parameters were measured, mainly including air temperature, RH, and CO_2 concentration. CO_2 is often used as a surrogate to evaluate indoor ventilation rate and indoor infection risk [34, 35]. During the measurements, all the sensors were placed around the geometrical center of the testing room at the height of human breathing zone. The measurements were performed at a 1-min interval. The instruments used in the measurements and their uncertainties and ranges are listed in Table 2.

2.2. Questionnaire surveys

Questionnaire surveys were conducted to investigate the occupants' response to indoor thermal and airflow sensation, and the data was collected by distributing questionnaires to the occupants in the measured buildings. The questionnaire mainly consisted of two parts: 1) anthropometric data of occupants, including gender, sex, and height; 2) occupants' sensation towards thermal environment, air speed and indoor air quality. The ASHRAE 7 - point scale (−3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm and +3 hot) was used to evaluate the thermal sensation vote (TSV). A 3 - point scale was adopted to evaluate airflow sensation, including "Want higher", "No change" and "Want smaller". For IAQ, a 7-point scale including −3 "Very bad", "Bad",
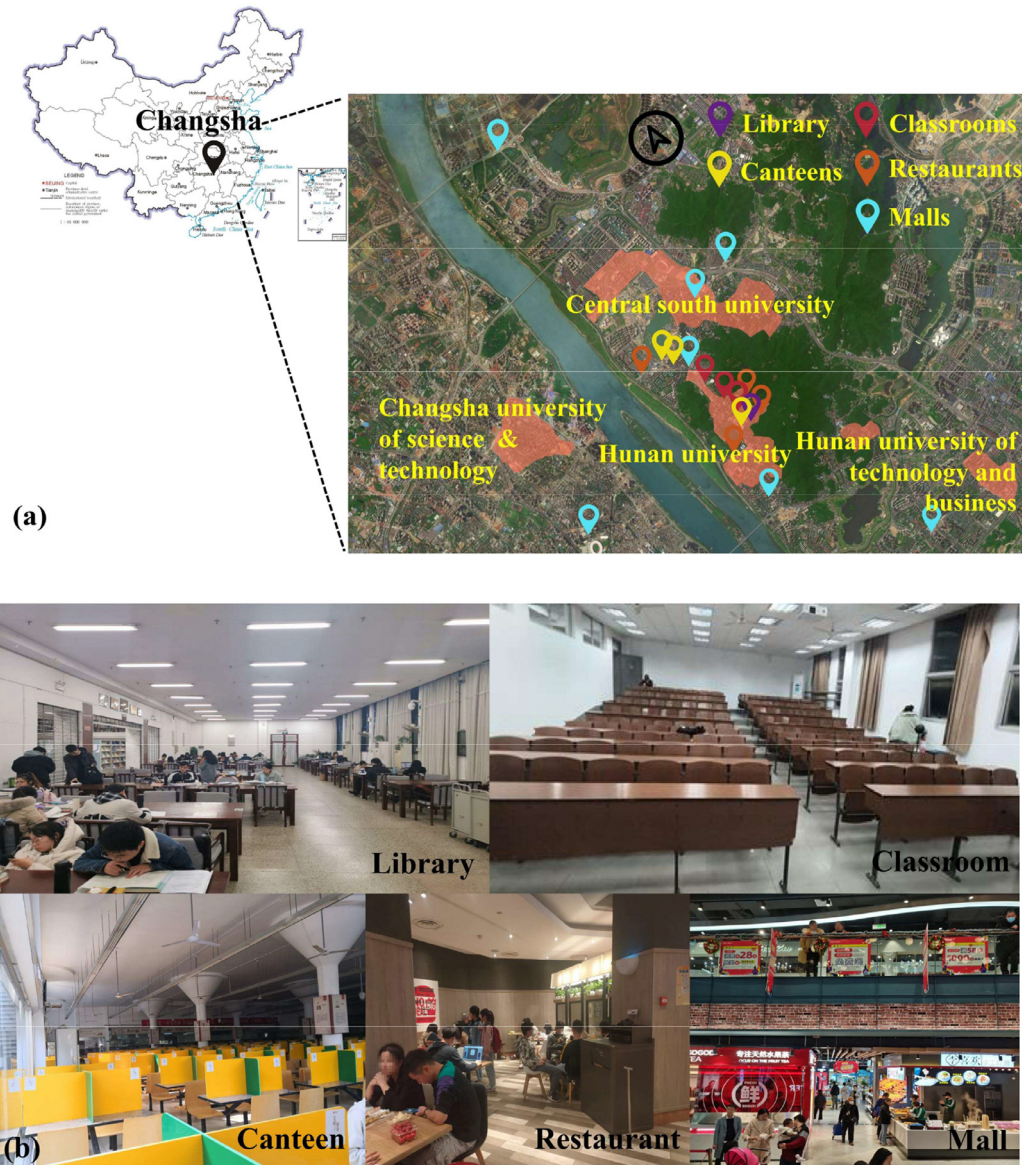
Fig. 1. (a) Locations of on-site measurements and (b) indoor environments of the studied buildings.

Table 2
Detailed information of measuring instruments.

Physical parameter	Instrument	Range	Accuracy
Indoor air temperature	HOBO	−20 - 70 °C	± 0.21 °C (0 - 50 °C)
Indoor relative humidity	temp/RH	15 - 95%	25 - 85% ± 3.5%
	loggers		< 25% or > 85% ± 5%
CO_2 concentration	Telaire 7001	0 - 10,000 ppm	± 50 ppm or ± 5% of readings in the range of 0 - 2500 ppm

"Slightly bad", "Neutral", "Slightly good", "Good", and "Very good" was adopted. The questionnaire is described in Table 3.

We prepared two forms of questionnaires, namely internet and paper based, for respondents to choose. For internet one, a link was created by a questionnaire platform (called questionnaire star) and sent out through social media. The results of questionnaires completed via internet were collected automatically by the platform, and those completed through paper were collected manually. The respondents were randomly selected from the studied public buildings, and they were all lived in Changsha. The questionnaires were continuously collected from October 26th to December 30th. Table 4 lists the anthropometric data of the respondents. A total of 3292 responses were collected, of which

2220 questionnaires were valid. The corresponding respondents of both genders are approximately evenly distributed, and 90.9% of respondents were in the age between 18 and 30 years old.

3. Results

3.1. Indoor air temperature, rh and air speed

Indoor thermal environment has a significant impact on occupants' comfort. In this section, both the results of measurements and questionnaire surveys are presented. Fig. 2 displays the measured air temperature and RH of the five types of public buildings. The comfort zones are

Table 3

Subjective questionnaire.

Gender			Age		Height		Weight	
Thermal sensation	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	
Airflow sensation	Want higher	No change	Want smaller					
IAQ	Very bad	Bad	Slightly bad	Neutral	Slightly good	Good	Very good	

Table 4

Anthropometric data of the respondents.

Gender	Number	Age (years old)		Height (cm)		Weight (kg)	
		Range	Mean	Range	Mean	Range	Mean
Male	1087	10 - 57	23.4	140 - 190	175.6	33 - 90	69.7
Female	1133	10 - 60	22.6	145 - 178	163.4	40 - 82	55.2
Total	2220	10 - 60	23	140 - 190	169.4	33 - 90	62.3
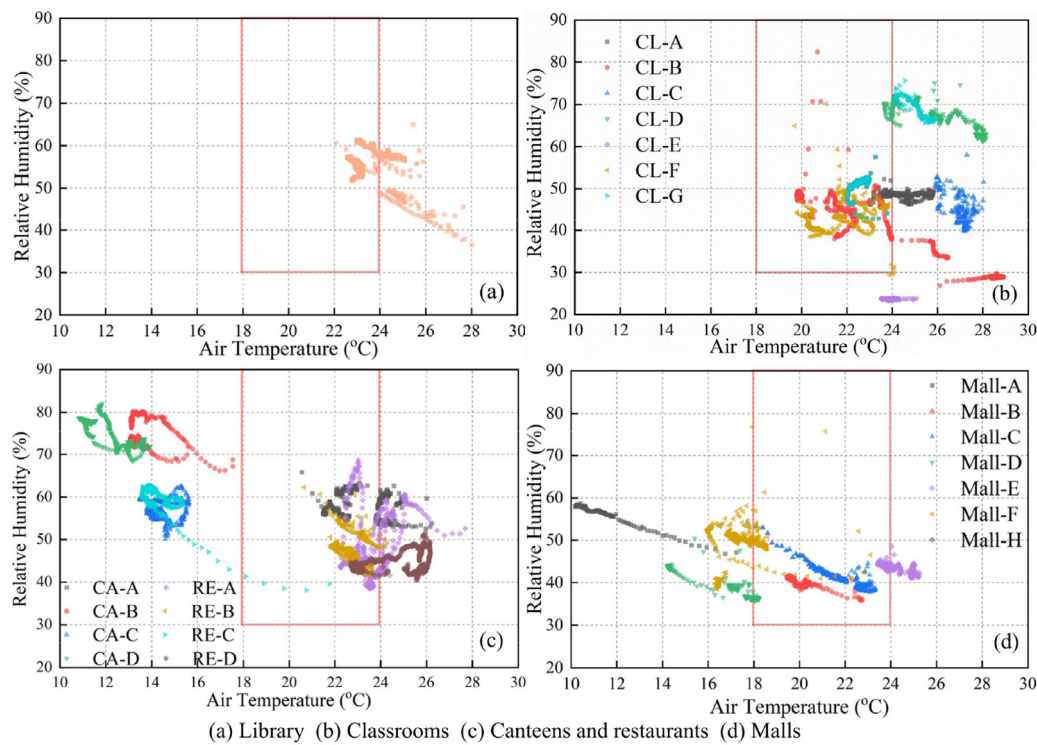
Fig. 2. Indoor air temperature and RH distributions in the studied public buildings.

circled with red rectangular based on Chinese design code for heating, ventilation and air conditioning of civil buildings (GB/T 50,376–2012) [36], which are air temperature ranging between 18 - 24 °C and RH being above 30%. It was found that a considerable part of the points was outside the comfort zones. In library and classrooms, which were heated by air conditioners, indoor air temperature was relatively high, with an average temperature of 23.6 °C and 24.1 °C, respectively. The high indoor air temperature was mainly caused by three reasons: (a) air conditioners were controlled by occupants, and were usually adjusted to high air temperature; (b) the windows and doors were kept closed during the operation of air conditioners; and (c) the density of occupants in classrooms were high up to 0.9 person/m^3. Noticeable differences appeared between the canteens and restaurants. Similar with library and classrooms, high air temperature and low RH were shown in the restaurants in university town, where air-conditioners or fan coil units were used for heating. The naturally ventilated canteens presented a low air temperature and high humidity environment. As for malls, the indoor

air temperature depended on the condition if the mechanical ventilation was well running. The air temperature in Mall-A was as low as 10.2 °C, which was due to the low ventilation rate in the morning.

In terms of the questionnaire results, the indoor thermal sensation of the studied public buildings was generally satisfied, as shown in Fig. 3. In Fig. 2, the air temperature in the canteens was relatively low. However, only 12.2% of respondents of canteens found the indoor thermal environment cold, and 85.3% of respondents accepted the indoor thermal environment. This discrepancy between measured results and surveyed data should be attributed to the fact that diners wore typical winter clothes in canteens and ate to kept warm. It was noted that the questionnaires of malls were mostly distributed to respondents in afternoon, hence, the thermal sensation related to the morning of Mall-A was not shown.

Airflow is also an important indicator that affects the thermal comfort perception of occupants [37]. The airflow results were obtained by questionnaire results. As shown in Fig. 4, the percentage of peo-
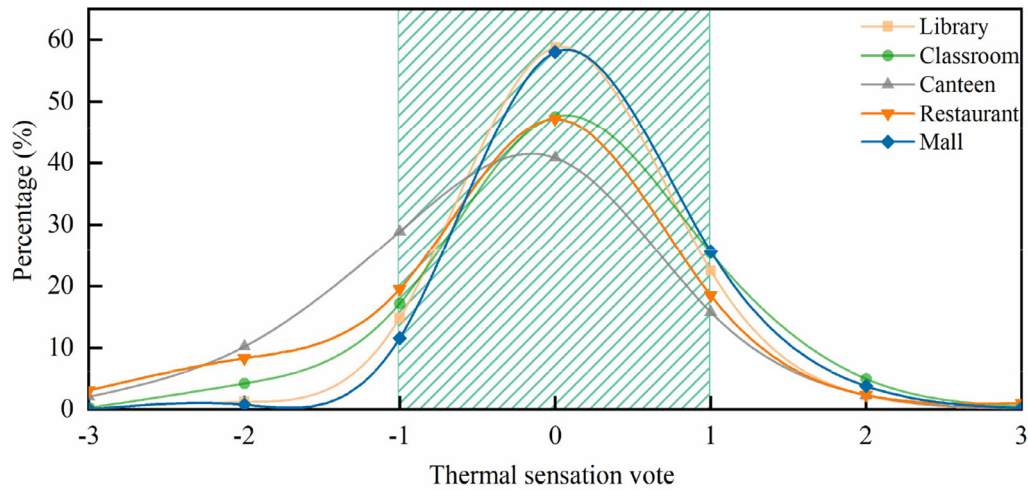
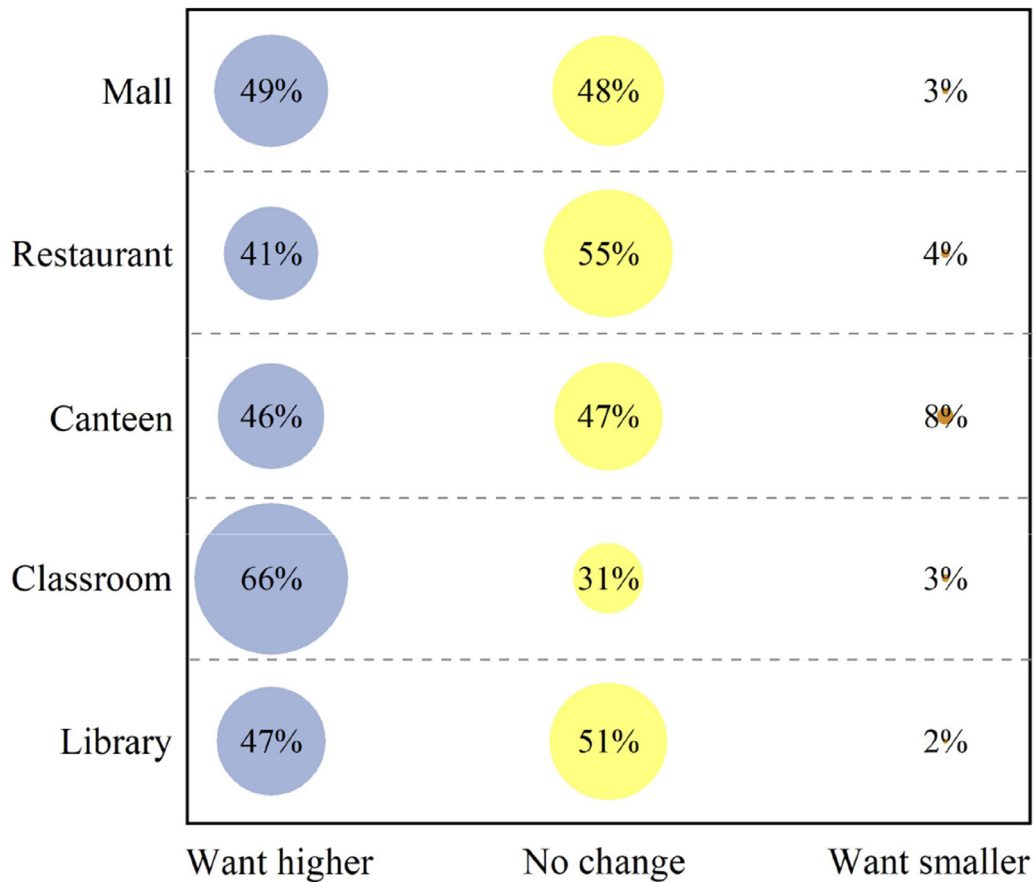**Fig. 3.** Overall thermal sensation vote in the studied public buildings.

Fig. 4. Occupants' response to air movement preference.

ple choosing "Want higher" and "No change" was almost the same in malls, canteens, and library, while that of people in restaurants choosing "Want higher" was lower than the "No change". As for classrooms, more than half of students (66%) chose "Want higher", indicated that the indoor air was really stagnated and students expected a higher air movement.

3.2. Indoor air quality

CO$_2$ concentration is an important indicator of IAQ and ventilation condition. ASHRAE Standard 62–1989 [38] suggested that indoor CO$_2$ concentration should be below 1000 ppm. Fig. 5 presents the box plots of CO$_2$ concentration distribution in five types of public buildings. It was observed in library, classrooms, restaurants and malls, the average CO$_2$ concentrations all exceeded the limited value, indicating insufficient ventilation. In the naturally ventilated canteens, the CO$_2$ concentration was low with the average value of 683 ppm, indicated that natural ventilation was an efficient way of maintaining a good IAQ. It was also demonstrated that, in classrooms and restaurants, the CO$_2$ concentration was concentrated. Long-term stay in such indoors environment is strongly associated with the prevalence of illness and sick building syndrome (SBS) [39].
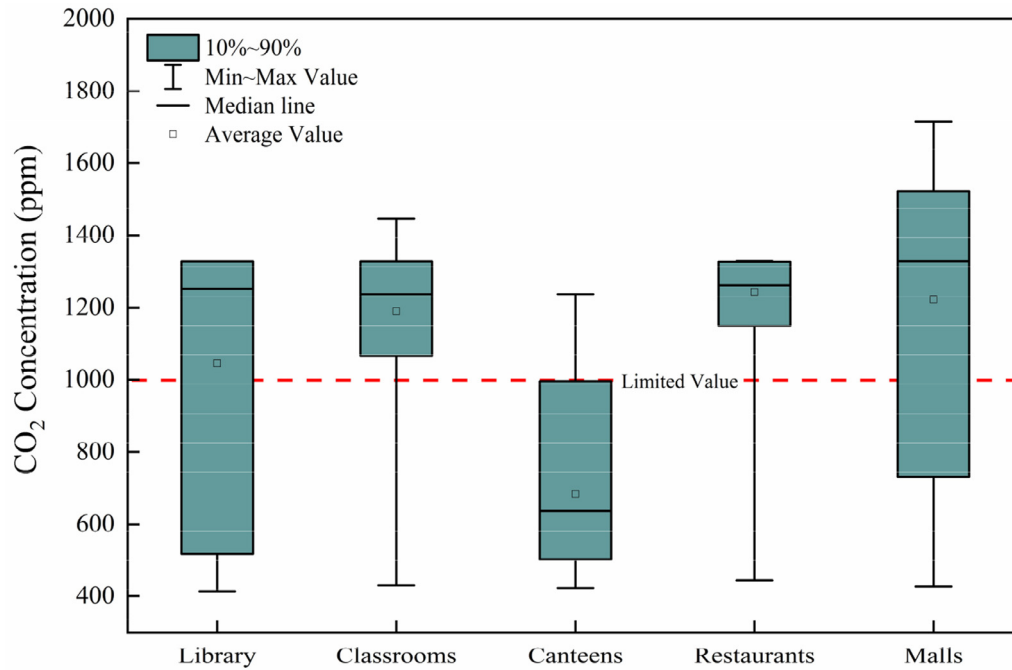
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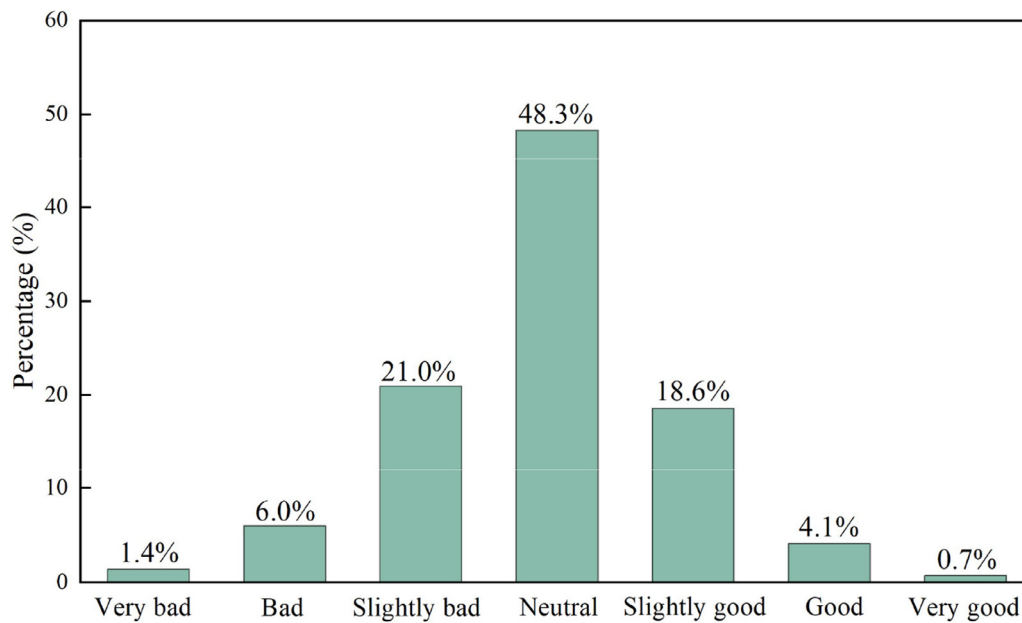**Fig. 5.** CO$_2$ concentration in the studied public buildings.

Fig. 6. Respondents sensation for IAQ.

In terms of the questionnaire results, as shown in Fig. 6, although CO$_2$ concentration exceeded the limited value, there were 47.8% of respondents considered IAQ neutral, and 23.4% of respondents choose 1, 2 and 3, expressing satisfaction with IAQ, indicated that the respondents were not sensitive to IAQ. In such a regard, it was implied that when majority of occupants felt the IAQ was stuffy, the indoor pollutant concentration had already reached a relatively higher level. Overall, if natural ventilation via doors and windows was controlled by occupants, the indoor occupants would mostly be high, as they tended to keep the doors and windows closed for improving thermal comfort.

4. Risk evaluation of infecting COVID-19

Direct measurements of virus-laden aerosols are extremely difficult. Currently, tracer gas simulation is considered as a suitable technology to investigate airborne transmission in built environment under certain conditions [40, 41], of which CO$_2$ concentration is widely used as an indicator and index [42–44]. In the public buildings of university town, the indoor CO$_2$ concentration is produced only by human exhalations, which is thus used as the tracer gas to evaluate SARS-CoV-2 transmission risk in this study. Some studies and guidelines have suggested limiting
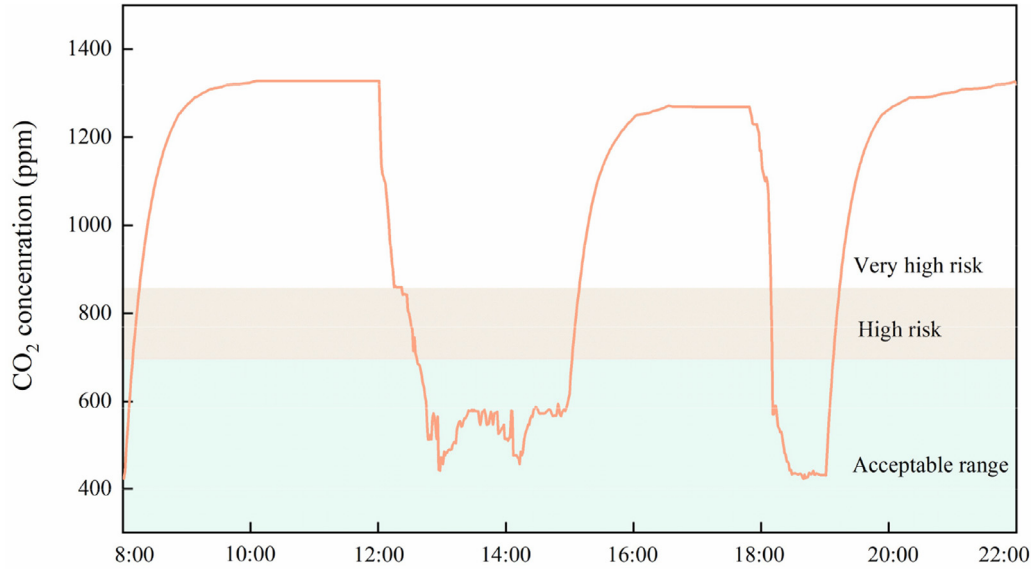
Fig. 7. Evolution of CO_2 concentration in the library.

indoor CO_2 concentration to mitigate the transmission risk of SARS-CoV-2 in universities. Taiwan Ministry of Education [45] suggested that the indoor CO_2 concentration should be below 1000 ppm, and REHVA [16] proposed two warning grades with CO_2 concentration at 800 ppm and 1000 ppm for classrooms and restaurants. However, with multiple public buildings in university town, it is not suitable to use one single standard for all types of buildings. Peng and Jimenez [46] developed a CO_2 concentration based calculation method to evaluate indoor airborne transmission risk of SARS-CoV-2, the analytical expressions can be applied to various typical indoor environment. This calculation method is applied in this study, which is shown in Eq. (1):

$$\Delta c^*_{CO_2} = \frac{PNE_{p,CO_2}}{(1-\eta_{im})\eta_I(N-1)E_p(1-m_{ex})(1-m_{in})B} \times \frac{\frac{1}{\lambda_0} - \frac{1-e^{-D\lambda_0}}{D\lambda_0^2}}{\frac{1}{\lambda} - \frac{1-e^{-D\lambda}}{D\lambda^2}} \quad (1)$$

where Δc_{CO_2} is the excessive CO_2 concentration beyond the ambient CO_2 concentration (ppm); P is the infection risk, which is associated with the excess CO_2 concentration; D is the duration of the event (h), and its value varies with different events; N is the number of indoor occupants, E_{p,CO_2} is the exhalation rate of each occupant (m^3/h), which is set according to Persily and de Jonge' study [47]; η_{im} is the SARS-CoV-2 immune rate of individual, which is equal to 0; η_I is the probability of an individual being an infector, which is set to 0.001; E_p is the SARS-CoV-2 exhalation rate of 1 infector (quanta/h), the value is various according to the physical and vocal levels [16, 46]; m$_{in}$ and m_{ex} are respectively the mask filtration efficiency for inhalation and exhalation, and their values are determined based on the condition whether or not to wear a mask and the type of mask. In this study, we assumed occupants were wearing ordinary medical mask in public buildings of university town, and the values are set based on Davies et al. [48], except in canteens and restaurants, where m$_{in}$ and m_{ex} are equal to 0; B is the breathing rate of the susceptible person (m^3/h), which is different for varieties of activities [49]; λ is the first-order overall rate constant of SARS-CoV-2, and λ_0 is the first-order loss rate coefficient of excess CO_2. The detailed information of the values of the parameters in Eq. (1) is presented in Table 5.

Based on the $\Delta c^*_{CO_2}$ and the local outdoor background CO_2 concentration (that was 422 ppm during the measurement periods), a 3-level-risk classification scheme was developed, where the P (infection risk) below 0.02%, equal to 0.03%, and above 0.03% was classified as "Acceptable range", "High risk" and "Very high risk", respectively. The eventual

boundaries of the indoor CO_2 concentration for different classification schemes are presented in Table 6.
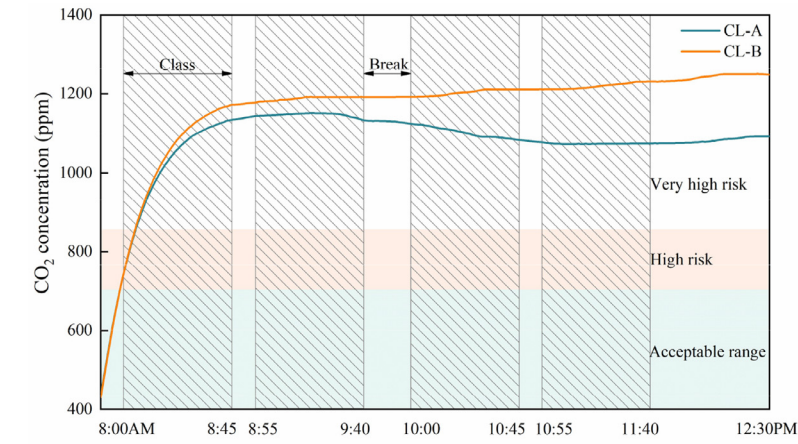
4.1. Library

The real-time monitoring of CO_2 concentrations can provide information for establishing effective ventilation strategies to reduce the spread of SARS-CoV-2 [50]. The monitor began at 8:00 a.m., which was the time the library opened, and the duration was 12 h until the library closed. During the monitoring, the air conditioners continued operating at heating mode. The "acceptable range", "high risk" and "very high risk" are plotted in the figure. It was observed that CO_2 concentration quickly rose to 1327 ppm in the first 2 h, and was stabled at a value until 12 p.m. When majority of students left for lunch, a 50-min break can let the CO_2 concentration drop rapidly down to level close to the outdoor concentration. The increase of CO_2 concentration occurred again in the afternoon and evening. Overall, the library was almost at "very high risk" and "high risk" conditions, except during the lunch and dinner times. Fig. 7

For libraries, the "Guidelines for the Prevention and Control of COVID-19 in Higher Education Institutions" issued by the Chinese Ministry of Education recommends reducing the number of entrances, checking visitor's body temperature, wearing face masks, and keeping social distance. However, the measured results showed the insufficient ventilation and thus a high risk of cross-infection. The following suggestions may be useful to reduce the risk. Firstly, intermittent occupancy can be applied, which means that occupants should leave periodically to reduce the generation of CO_2 (possibly viruses). Secondly, centralized mechanical ventilation should be installed in the library to provide more fresh air. If centralized mechanical ventilation cannot be installed, windows should be open regularly by designated personnel. Thirdly, real-time monitoring and displaying the IEQ (e.g. real-time CO_2 concentration) is a recommended solution. A warning value of IEQ indicator can be defined to remind indoor occupants to leave, provided that increasing fresh air supply is impossible. It is easy to apply these approaches in practice, not only for libraries in universities, but also for all types of public buildings investigated in this study.
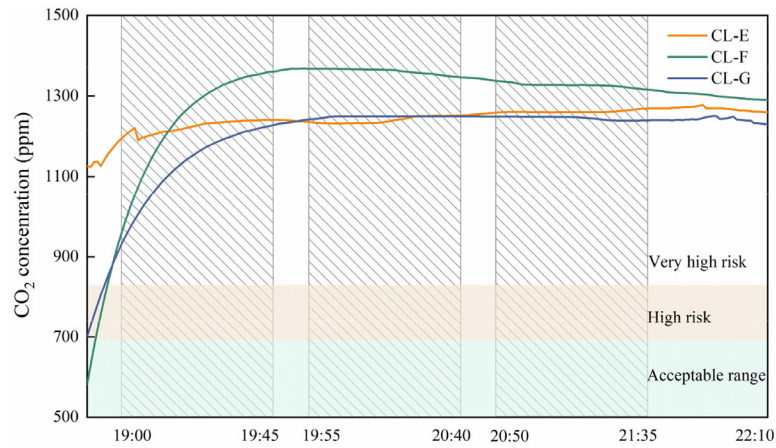
4.2. Classroom

Fig. 8 presents the measured CO_2 concentration during morning, afternoon, and evening classes in classrooms. The morning classes began
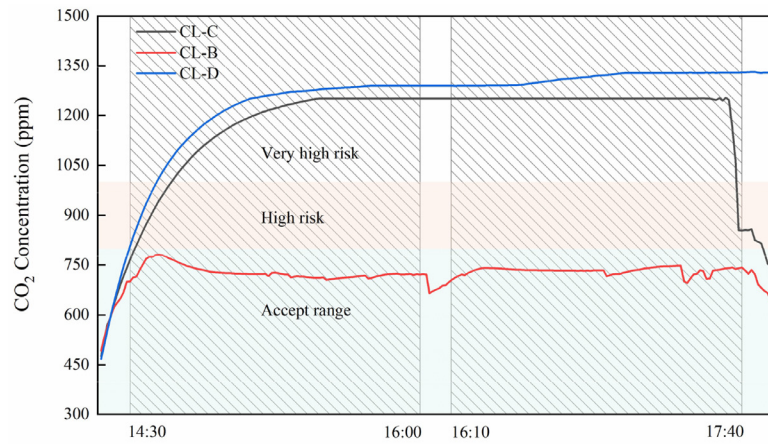
Fig. 8. Evolution of CO_2 levels during different time of the classrooms.

Table 5
Values of the calculated parameters in Eq. (1).

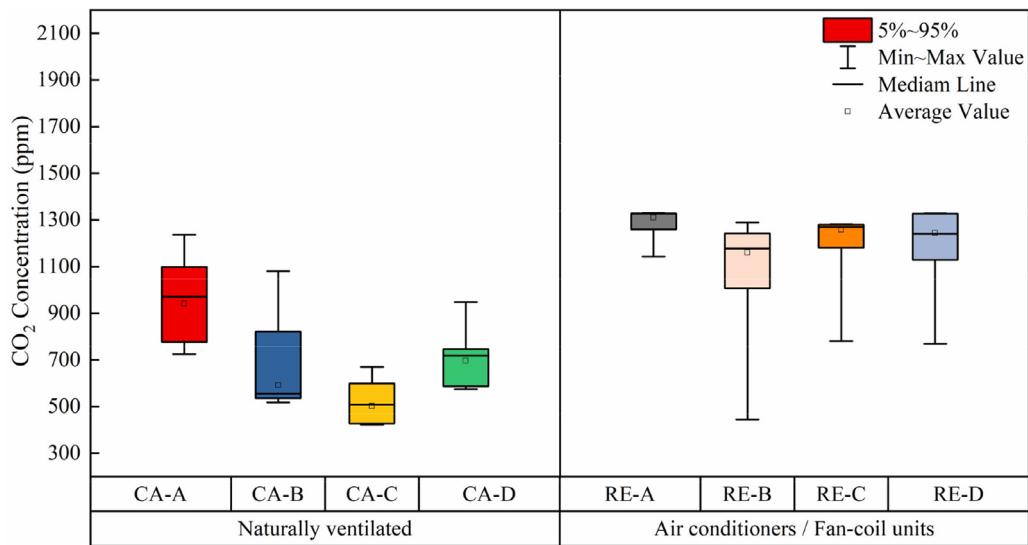| Building type	N	E_p	E_{p,CO_2}	B	η_{im}	η_I	D	m_{in}	m_{ex}	λ_0	λ
Library	40	100	0.0202	0.516	0	0.001	4	0.3	0.5	3	3.92
Classrooms	40	100	0.0202	0.516			3	0.3	0.5		
Canteens and restaurants	100	100	0.0342	0.516			0.5	0	0		
Malls	100	40.7	0.0275	0.98			8	0.3	0.5		

Fig. 9. CO_2 concentration in canteens in universities and restaurants in the university town.
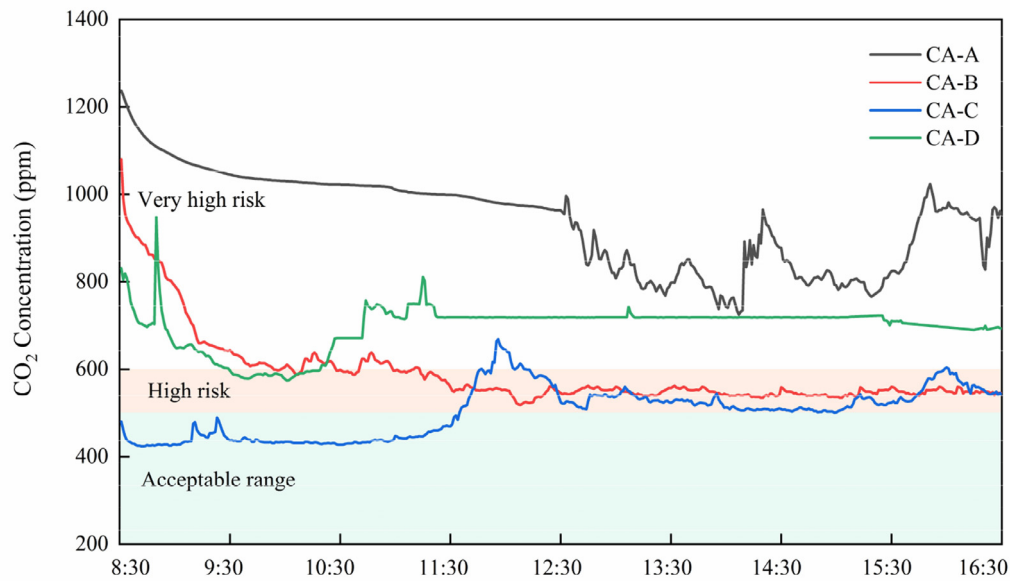

Fig. 10. Evolution of CO_2 concentration in the naturally ventilated canteens.

Table 6
Risk classification scheme based on CO_2 concentration.

Type	Acceptable range	High Risk	Very High Risk
Library	<714	<860	>860
Classroom	<714	<860	>860
Canteens and restaurants	<540	<599	>599
Malls	<933	<1187	>1187

at 8:00 a.m. and ended at 11:40 a.m., which contained 4 sessions and 3 breaks, with each session lasted for 45 mins. The first and third break were 10 mins, the second break was 20 mins. In the afternoon, the classes began at 14:30 p.m. and dismissed at 17:40 p.m., with 1 break from 16:00 to 16:10 p.m. The classes in the evening began at 19:00 p.m. and ended at 21:35 p.m., which included two 10-min breaks. During the classes, doors and windows were mostly kept closed and air conditioners were operated continuously with heating mode to provide a warm indoor thermal environment.

The CO_2 generation rate was constant during the class, as the indoor occupants stayed the same during the class time. The initial value depended on the room ventilation, and five out of seven classrooms (71.4%) showed that the initial CO_2 concentrations closed to outdoor concentration, The average stabled concentration in the classrooms in the morning, afternoon, and evening was 1117 ppm, 1093 ppm, and 1242 ppm, respectively, with a slight increase of 125 ppm from morning to evening. Such high CO_2 concentration meant that, on average, 93.7% of class time was at the level of "very high risk", which was basically caused by the high occupant density (0.9 person/m^3) and insufficient ventilation. Note that the low CO_2 concentration in CL-B in the afternoon was due to the continuous opening of the windows at a large angle (approximately half open). Almost negligible influence of break times on the reduction of CO_2 concentration was found, as students usually stayed on their seats even during the break times.

The classroom prevention and control measures recommended by the Chinese Ministry of Education include mainly wearing face masks, keeping social distance, and natural ventilation via open windows and doors for at least three times per day. During the measurements, it
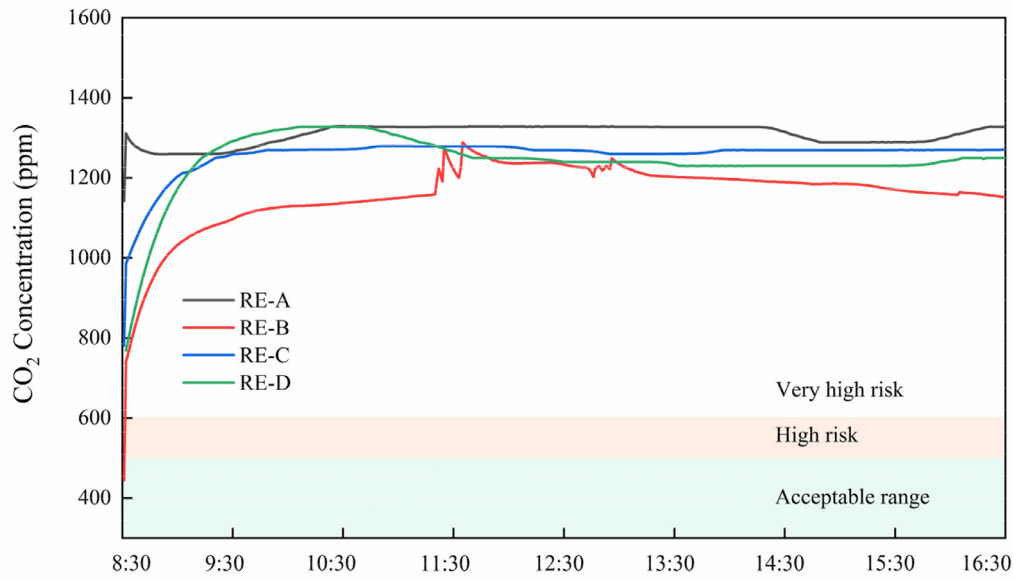
Fig. 11. Evolution of CO_2 concentration in the air-conditioned restaurants.
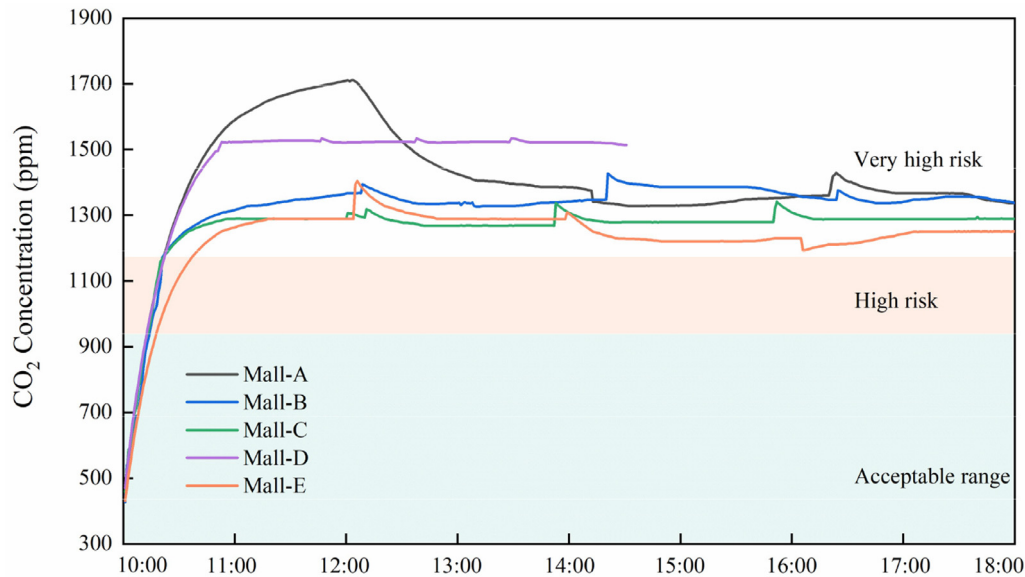

Fig. 12. Evolution of CO_2 concentration in the constant air volume mechanically ventilated malls.

was observed that the three recommendations were all not well followed, posting potential risk of cross-infection. Apart from these recommended officially, the following suggestions are made based on the present study. Firstly, students should leave the classrooms during the break times, so as to reduce the generation and accumulation of exhaled air. Secondly, personnel (could also be an in-class student) should be designated to manage the opening of windows and doors during classes, during break times, and after classes. If possible, the windows can be equipped with motorized window-opening valve, so that the real-time motoring can be coupled with the window-opening valve to manage the opening of windows automatically. This should be able to considerably improve the ventilation.

4.3. Canteen and restaurant

Fig. 9 shows the indoor CO_2 concentration in canteens in universities and restaurants in the university town. From the figure, it was observed that indoor CO_2 concentration in university canteens was gen-

erally much lower than restaurants. The average value of CO_2 concentration in restaurants was as high as 1242 ppm, while it was 683 ppm in canteens. The major reasons for this large difference in CO_2 concentration between restaurants and canteens included difference in space volume and natural ventilation rate. Canteens in universities have high ceilings and thus large space volumes to buffer the increase of CO_2 concentration, where the doors are always open for students entering and leaving. In contrast, restaurants usually have confined spaces and have the doors closed as much as possible for maintaining a thermally comfortable environment. Such a comparison indicates the importance and efficiency of natural ventilation.

As the face masks are inapplicable when dining, the canteens and restaurants must have relatively low CO_2 concentration to maintain a safe indoor environment. Fig. 10 presents the evolution of CO_2 concentration in canteens and restaurants. From the figure, two important remarks can be made. Firstly, the CO_2 concentration in the canteens did not increase largely during lunch time. An increase of CO_2 concentration during lunch time for around 200 ppm was observed in CA-C
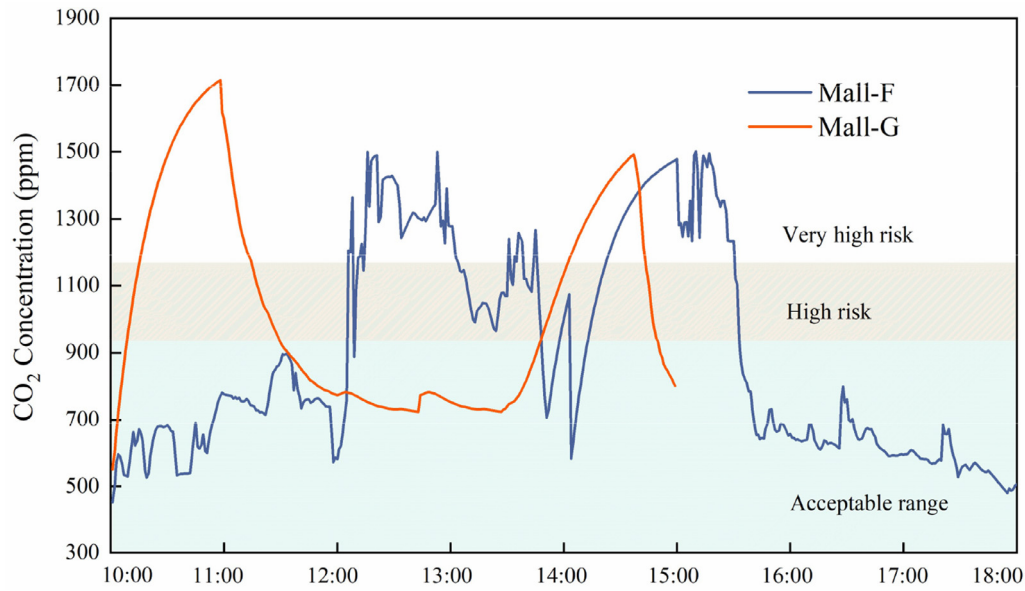
Fig. 13. Evolution of CO_2 concentration in the demand control mechanically ventilated malls.
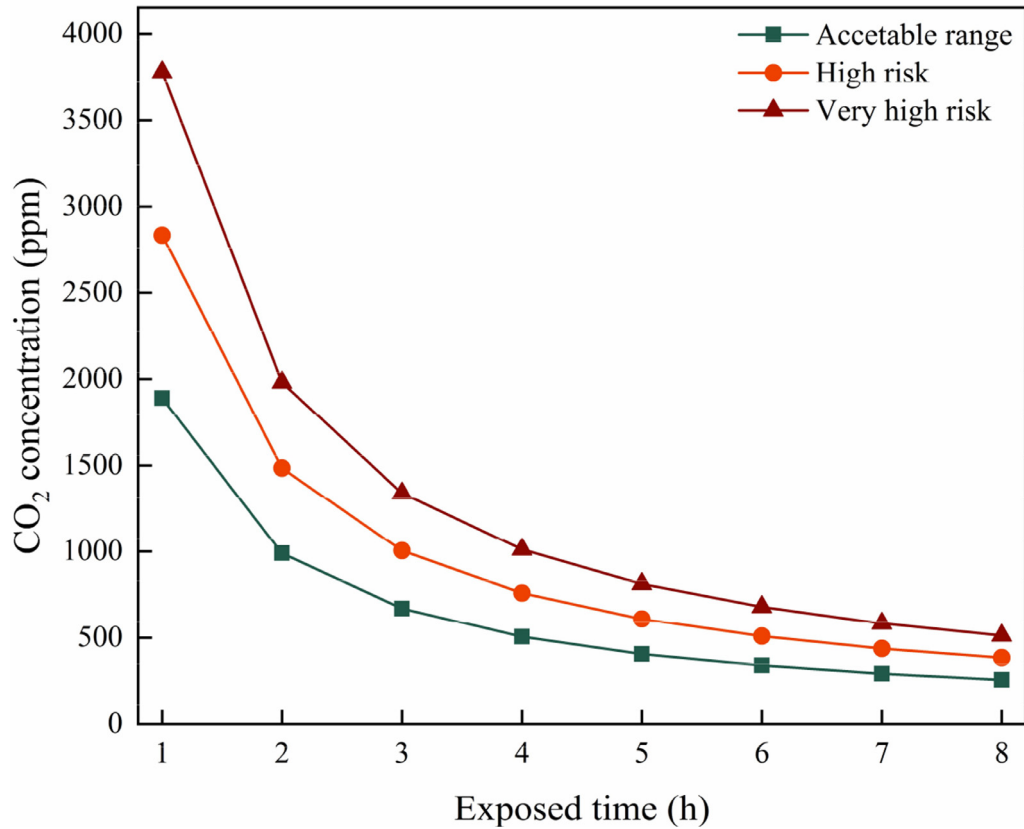

Fig. 14. Relationship between the threshold value of excessive CO_2 concentration and safe exposed time.

and CA-D, and such an increase was not found in another two canteens. The reason was that the doors of the canteens were usually open during lunch time (also dinner time) and closed in other time, especially during the non-business time, which, again, demonstrates the effect that natural ventilation had on reducing infection during people gathering. Secondly, it was also observed that natural ventilation alone cannot reduce indoor CO_2 concentration to a healthy level. In terms of duration, the percentage of "acceptable range" for three out of four canteens were

lower than 15%, indicated that mechanical ventilation was required to assist natural ventilation. The restaurants in the university town were installed with air-conditioners or fan-coil units to condition the indoor air temperature. Outdoor air was introduced only through the doors that were opened from time to time. As depicted in Fig. 11, the ventilation in these restaurants was rather poor, and the stable concentration value for RE-A reached 1309 ppm, which was much higher than the acceptable range.

As suggested by state council [51], the canteens should take appropriate measures to mitigate transmission risk, including checking customers' body temperature, keeping social distance, and extending the service time to avoid gathering. Apart from these measures, ventilation must be paid more attention. If natural ventilation is possible, intermittent natural ventilation through open windows or doors is strongly suggested. Mechanical ventilation systems are also suggested, in order to overcome the degrading of indoor thermal environment due to natural ventilation.

4.4. Mall

The monitors began at the opening time for malls at 10 a.m., and lasted for at least 4 h. The evolution of the CO_2 concentration was divided into two groups and shown in Fig. 12 and Fig. 13. The ventilation strategy constant air volume (CAV) was used in the malls shown in Fig. 12. The CO_2 concentrations were dramatically increased since the opening of the malls. The average steady value of CO_2 concentration in these malls was 1336 ppm, and the average time exposure to "very high risk" accounted for 94.0%. One reason for the relatively high CO_2 concentration in Mall-A, especially during the morning, was the incomplete operation of the mechanical ventilation systems, which was also supported by the measured results of air temperature, as described in Section 3.1.

Demand control ventilation (DCV) was used in Mall-F and Mall-G, as displayed in Fig. 13. DCV is an energy efficient ventilation strategy based on the sense of the indoor parameters, including particularly CO_2 concentration [52, 53]. Once the concentration is higher than the set value, the ventilation rate is increased to reduce excessive CO_2. ASHRAE and REHVA suggested that DCV should be disabled during the pandemic [16, 54] to avoid insufficient ventilation. However, it was observed from the measurements that the malls with DCV had, on average, lower indoor CO_2 concentration. In fact, for DCV systems, lowering the setpoint of CO_2 concentration or other IEQ indicators could result in a safe indoor environment. To mitigate the transmission risk in malls, the number of customers should be limited and ventilation should be sufficient.

Above classification scheme for the transmission risk of malls, was based on the assumption that the occupants stay in malls for 8 h. However, except for the staffs in the malls, customers rarely stay there for such a long time. Therefore, the threshold values of CO_2 were recalculated by Eq. (1) according to different durations. Fig. 14 shows the excessive CO_2 threshold concentration and exposure durations in affecting COVID-19 transmission risk. It was obvious that the threshold value of CO_2 concentration was lower if the exposed duration was longer. As measured results showed that the average concentration in the malls was 1336 ppm, which means that it was relatively safe for customers to stay in the malls for less than 2 h.

5. Summary and recommendations

In order to reveal IEQ condition and airborne transmission risk in public buildings in the university town during the pandemic and then to provide suggestions for improvements, on-site measurements of indoor air temperature, RH, and CO_2 concentration were conducted in some public buildings in a university town in the winter 2020 in Changsha. The transmission risk was predicted using a 3-level transmission risk scheme that was developed based on indoor CO_2 concentration. In addition, questionnaire surveys on the thermal sensation, air speed, and IAQ were performed.

Except for malls, the measured public buildings did not have mechanical ventilation systems. The CO_2 concentrations in those buildings without adequate natural ventilation were found to be rather high, with the average value of 1045 ppm in library, 1151 ppm in classrooms, 1242 ppm in restaurants, and 1057 ppm in malls. The percentage time of "very high risk" for infectious transmission in library, classrooms,

restaurants, and malls were 68.7%, 81.8%, 99.9%, and 75.7%, respectively. University canteens had relatively low CO_2 concentration (on average 683 ppm) and thus transmission risk, due to its large space volume, short service periods, and continuous natural ventilation. In general, inadequate ventilation should be a common problem in the public buildings in university town in China and improvements are urgent to be made.

Although mitigation measures of transmission have been recommended by the governmental departments and professional societies, the measured results show that they are not well implemented in the public buildings in university town. Apart from these officially recommended mitigation measures, based on the present measurements and surveys, the following suggestions may be proposed. Firstly, the high occupant density was found in all public buildings of university town, thus we propose three feasible approaches: (a) intermittent occupancy by setting compulsory breaks in libraries and classrooms, (b) prolonged service time in canteens and restaurants, and (c) limited visiting time in malls for maximal 2 h. Secondly, intermittent natural ventilation should be either managed by designated personnel or by automatic control systems to ensure the necessary operational frequency and time. Thirdly, real-time monitoring devices should be widely installed in occupant zones of public buildings and display screens should be installed to inform occupants of the indoor air condition. Fourthly, DCV should be able to adjust down the setpoint of indicators (such as CO_2 concentration) to allow its use during pandemics.

The present study was limited to a climate zone with hot summers and cold winters, while the on-site measurements and questionnaire surveys were performed during only a winter. CO_2 concentration was monitored to indicate the ventilation condition, but the ventilation rate in these investigated spaces was not measured. The recommended mitigation measures were based only on the calculation of airborne transmission risk, without analyzing their energy consumption.

Credit authorship contribution statement

Yufan Chang: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Xiaochen Zhang**: Investigation, Methodology, Data curation, Formal analysis. **Ge Song:** Investigation, Methodology, Data curation. **Jing Liu:** Investigation, Data curation. **Chen Lin:** Investigation. **Jinjun Ye:** Investigation. **Jie Hu:** Investigation. **Lei Tang:** Investigation. **Zhengtao Ai**: Conceptualization, Methodology, Funding acquisition, Resources, Writing – review & editing.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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